



## Enhancing mustard productivity through mineral nutrient management in Bundelkhand region of Uttar Pradesh

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### Abstract

A field experiment was conducted during *Rabi* season of 2024-25 at the Research Farm of Rani Lakshmi Bai Central Agricultural University, Jhansi, Uttar Pradesh, India, under irrigated conditions of the Bundelkhand region to evaluate the effect of integrated nutrient management (INM) on the productivity and profitability of Indian mustard (*Brassica juncea* L.). The experiment was laid out in a split plot design comprising sixteen treatment combinations with four NPK fertility levels as main plots and four sulphur (S), zinc (Zn), and boron (B) combinations with and without farmyard manure (FYM) enrichment in subplots. The results demonstrated that integrated nutrient management significantly improved growth, yield attributes, yield, and economic returns. Application of 150% recommended dose of fertilizer (180:90:90 kg N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O ha<sup>-1</sup>) recorded maximum plant height (216.8 cm), siliquae per plant (149.1), seeds per silique (19.3), seed yield (2886 kg ha<sup>-1</sup>), bundle weight (9229 kg ha<sup>-1</sup>), net return (Rs. 126,637 ha<sup>-1</sup>), and benefit-cost ratio (2.81). Among secondary and micronutrient treatments, application of 40 kg S + 5 kg Zn + 1 kg B ha<sup>-1</sup> enriched with 500 kg FYM ha<sup>-1</sup> produced the highest seed yield (2267 kg ha<sup>-1</sup>), bundle weight (7233 kg ha<sup>-1</sup>), gross return (Rs. 134,923 ha<sup>-1</sup>), net return (Rs. 91,987 ha<sup>-1</sup>), and benefit-cost ratio (2.10). Principal Component Analysis further revealed a strong positive association of higher NPK levels integrated with S, Zn, B, and FYM with yield, nutrient uptake, and quality traits. Thus, integrated application of 150% RDF along with 40 kg S + 5 kg Zn + 1 kg B ha<sup>-1</sup> enriched with 500 kg FYM ha<sup>-1</sup> emerged as the most effective nutrient management strategy for enhancing productivity and profitability of Indian mustard under irrigated Bundelkhand conditions.

**Keywords:** Bundelkhand, INM, nutrients, mustard, secondary and micro nutrients, productivity

### Introduction

Indian mustard (*Brassica juncea* L.) is one of the most important edible oilseed crop in India, contributing substantially to national oilseed production and nutritional security. India ranks as the third-largest producer of mustard after Canada and China, accounting for nearly 14% of global production. During 2023–24, rapeseed–mustard occupied 30.3% of the total oilseed area and contributed 33.2% of total oilseed production, with Indian mustard representing nearly 80% of the cultivated rapeseed–mustard area and the national average productivity of rapeseed-mustard (1443 kg/ha) exceeds the overall average for oilseeds (1314 kg/ha). Major mustard-producing states include Rajasthan (45.4%), Uttar Pradesh (14.2%), Madhya Pradesh (13.3%),

Haryana (10.8%), and West Bengal (6.0%). In Uttar Pradesh, the crop is cultivated over an area of 0.76 million hectares, yielding 1.03 million tonnes with a productivity of 1370 kg/ha (DRMR, 2024; MoA & FW, 2023). During 2022-23, rapeseed-mustard in Bundelkhand occupied 0.267 m ha area with production of 0.286 m tonne and productivity of 1071 kg ha<sup>-1</sup>, reflecting increased cultivation despite yield fluctuations (Directorate of Economics and Statistics, 2023). Despite its economic importance, the productivity of Indian mustard remains below its genetic potential due to nutrient depletion, soil degradation, and imbalanced fertilizer application, particularly under intensive cropping systems and rainfed agro-ecosystems (Kumar *et al.*, 2016; Meena *et al.*, 2025). Intensive agriculture and imbalanced fertilizer use have

accelerated multi-nutrient deficiencies in Indian soils, posing a major constraint to sustainable crop production. According to NAAS (2018), nearly 59% of Indian soils are deficient in available nitrogen, 49% in phosphorus, 46% in sulphur, 49% in zinc and 33% in boron, while potassium deficiency is comparatively less widespread. These widespread nutrient imbalances reduce nutrient-use efficiency, soil fertility and crop productivity, highlighting the need for balanced and integrated nutrient management strategies. The Bundelkhand region is characterized by inherently low soil fertility and widespread nutrient deficiencies. The soils are generally low in available nitrogen and phosphorus, medium to high in potassium, deficient in sulphur, and exhibit moderate to severe zinc deficiency, particularly under continuous cultivation and imbalanced fertilizer use. Excessive dependence on NPK fertilizers with inadequate replenishment of secondary and micronutrients has further aggravated deficiencies of sulphur (S), zinc (Zn) and boron (B), resulting in reduced soil fertility and crop productivity. Therefore, balanced nutrient management integrating macro-, secondary and micronutrients is essential for sustaining mustard production in this region.

Sustainable production of mustard requires balanced nutrient management that integrates primary, secondary and micronutrients. Nitrogen, phosphorus and potassium regulate vegetative growth, root development, photosynthesis and assimilate partitioning, thereby determining crop productivity. However, continuous use of NPK fertilizers without adequate supplementation of secondary and micronutrients has accelerated deficiencies of sulphur (S), zinc (Zn) and boron (B) in many Indian soils, reducing nutrient-use efficiency and crop performance (Singh and Singh, 2015; Yadav and Sarkar, 2019). Such hidden nutrient deficiencies have become a major limitation for achieving higher yield and oil quality in Brassica crops. Among secondary nutrients, sulphur is particularly important for mustard because of its high requirement for the synthesis of sulphur-containing amino acids, proteins, chlorophyll, vitamins and glucosinolates, which directly influence oil biosynthesis and seed quality (Karthikeyan and Shukla, 2008; Kumar *et al.*, 2017). Likewise, zinc functions as a structural and catalytic component of numerous enzymes involved in protein synthesis, auxin metabolism, chlorophyll formation and photosynthetic processes, whereas boron plays a critical role in cell wall development, carbohydrate translocation, pollen viability, fertilization and seed formation (Graham *et al.*, 1992; Islam and Anwar, 1994; Havlin *et al.*, 2013). Deficiency of these nutrients adversely affects reproductive development, nutrient uptake and assimilate translocation, leading to

poor silique formation, reduced seed set and lower productivity.

Integration of mineral fertilizers with organic nutrient sources has emerged as an effective strategy for restoring soil fertility and improving nutrient-use efficiency. Farmyard manure (FYM) enhances soil organic carbon, microbial activity, aggregation, cation exchange capacity and nutrient retention, while enriched FYM serves as an efficient carrier for secondary and micronutrients, ensuring their gradual release and improved availability to plants (Dotaniya and Meena, 2013; Chaudhary *et al.*, 2020). The combined application of balanced NPK with S, Zn and B through enriched FYM is therefore expected to improve crop growth, nutrient uptake and soil health more effectively than the application of individual nutrients alone. Although the individual effects of major and micronutrients on mustard have been widely investigated, information on their integrated application through enriched FYM under graded NPK levels remains limited. Considering the increasing occurrence of sulphur, zinc and boron deficiencies in mustard-growing soils and the importance of balanced nutrient management for sustainable mustard production, the present study was undertaken to assess the response of Indian mustard to different NPK fertilizer levels in conjunction with sulphur, zinc and boron applied through enriched farmyard manure and their effects on crop growth, productivity, nutrient uptake, quality attributes and economic returns under Bundelkhand conditions.

## Materials and Methods

### Experimental site

A field experiment was carried out during the *Rabi* season of 2024–25 at the Research Farm of Rani Lakshmi Bai Central Agricultural University, Jhansi, Uttar Pradesh. The experimental farm is located in the semi-arid region of Bundelkhand at 25°27' N latitude and 78°35' E longitude with an elevation of 271 m above mean sea level. The area experiences a subtropical climate characterized by hot summers and cool winters. The experimental soil was sandy loam in texture, slightly alkaline in reaction (pH 7.2) and had an electrical conductivity of 0.23 dS m<sup>-1</sup>. Initial soil analysis indicated low organic carbon (0.20%), available nitrogen (102.5 kg ha<sup>-1</sup>) and available phosphorus (7.42 kg ha<sup>-1</sup>), whereas available potassium (211.4 kg ha<sup>-1</sup>) was in the medium range. The soil also contained 4.8 ppm sulphur, 0.21 ppm zinc and 1.21 ppm boron.

### Experimental details and crop establishment

The experiment was laid out in a split plot design with three replications comprising sixteen treatment

combinations. Four levels of NPK fertilizers were assigned to the main plots, viz.,  $M_1$  : Control,  $M_2$  : 100% RDF (120 : 60 : 60 kg N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O ha<sup>-1</sup>),  $M_3$  : 125% RDF (150:75:75 kg ha<sup>-1</sup>) and  $M_4$  : 150% RDF (180:90:90 kg ha<sup>-1</sup>). The sub-plots received four combinations of secondary and micronutrients, namely  $S_1$  : 20 kg S + 2.5 kg Zn + 0.5 kg B ha<sup>-1</sup>,  $S_2$  : 40 kg S + 5 kg Zn + 1 kg B ha<sup>-1</sup>,  $S_3$  :  $S_1$  enriched with 500 kg FYM ha<sup>-1</sup> and  $S_4$  :  $S_2$  enriched with 500 kg FYM ha<sup>-1</sup>. Indian mustard variety ‘Giriraj’ was sown manually on 4 November 2024 in plots measuring 7 × 3 m<sup>2</sup> with a spacing of 30 × 10 cm. Basal fertilizers and FYM were applied according to treatment schedules before sowing, while recommended agronomic practices including irrigation, weed management and plant protection measures were uniformly followed throughout the crop season.

### Sampling and analysis

Growth parameters, yield attributes and seed yield were recorded from representative plants at harvest. Soil samples collected before sowing and after harvest were analyzed for fertility parameters, while representative seed and stover samples were oven-dried, ground and used for nutrient estimation. Available nitrogen, phosphorus and potassium in soil were estimated using the alkaline KMnO<sub>4</sub>, Olsen’s and flame photometric methods, respectively. Sulphur was determined by the turbidimetric method, zinc through atomic absorption spectrophotometry and boron by the azomethine-H method.

### Statistical analysis

The experimental data were analysed following analysis of variance (ANOVA) appropriate for a split plot design using R software (Version 4.4.1). Treatment means were separated using the critical difference (CD) test at the 5% level of significance. Principal component analysis (PCA) was further employed to examine the relationships among yield, nutrient uptake and quality-related traits.

## Results and Discussion

### Growth attributes and yield

The data demonstrated that growth and yield attributes of Indian mustard responded significantly to increasing fertility levels (Table 1). Application of 150% RDF (180 : 90 : 90 kg N : P<sub>2</sub>O<sub>5</sub> : K<sub>2</sub>O ha<sup>-1</sup>) significantly increased plant height (216.8 cm), primary branches (7.13 plant<sup>-1</sup>), secondary branches (13.25 plant<sup>-1</sup>), siliquae per plant (149.1), seeds per silique (19.3), seed yield (2886 kg ha<sup>-1</sup>) and bundle weight (9229 kg ha<sup>-1</sup>) over lower fertility levels, whereas control treatment recorded the lowest values (182.9 cm, 4.26, 7.43, 130.9, 15.8, 1352 kg ha<sup>-1</sup> and 4441 kg ha<sup>-1</sup>, respectively) as well as show in (Fig 1). The

superior performance under higher fertilizer application indicates that adequate nutrient availability throughout the crop growth period promoted vigorous vegetative growth and enhanced reproductive development, ultimately resulting in greater productivity. The improvement in plant height and branching under higher NPK levels may be attributed to the essential physiological functions of nitrogen, phosphorus and potassium in plant metabolism. Nitrogen promotes chlorophyll synthesis, protein formation and cell division, phosphorus enhances energy transfer, root proliferation and nucleic acid synthesis, while potassium regulates enzyme activation, osmotic adjustment and assimilate translocation. The combined action of these macronutrients improves photosynthetic efficiency, dry matter accumulation and source–sink relationships, thereby enhancing reproductive growth and seed production. Similar responses of balanced fertilization in mustard have been reported by Kumawat *et al.* (2014), Mir *et al.* (2021), Saroj *et al.* (2021), Amanullah *et al.* (2023), Patel *et al.* (2024), Bharati (2025) and Rajeev *et al.* (2025).

The integrated application of sulphur, zinc and boron along with FYM further improved growth performance. The treatment comprising 40 kg S + 5 kg Zn + 1 kg B ha<sup>-1</sup> enriched with 500 kg FYM ha<sup>-1</sup> ( $S_4$ ) recorded significantly higher plant height (203.9 cm), primary branches (6.57 plant<sup>-1</sup>), secondary branches (11.81 plant<sup>-1</sup>), seed yield (2267 kg ha<sup>-1</sup>) and bundle weight (7233 kg ha<sup>-1</sup>) compared with  $S_1$  (189.3 cm, 5.39, 9.92, 2018 kg ha<sup>-1</sup> and 6374 kg ha<sup>-1</sup>, respectively), emphasizing the importance of balanced secondary and micronutrient nutrition. Sulphur is an indispensable constituent of sulphur-containing amino acids and proteins, thereby supporting chlorophyll formation and metabolic activity. Zinc plays a pivotal role in auxin biosynthesis, enzyme activation, DNA and RNA synthesis and carbohydrate metabolism, resulting in improved root growth and nutrient uptake. Boron contributes to cell wall formation, sugar transport, pollen viability, hormone regulation and reproductive development, thereby enhancing seed formation and silique development. Farmyard manure (FYM) improves soil physical, chemical and biological properties by increasing soil organic carbon, microbial activity, nutrient mineralization and nutrient retention, thereby ensuring continuous nutrient availability throughout crop growth. The beneficial influence of integrated nutrient management observed in the present investigation corroborates earlier findings reported by Gupta *et al.* (2022), Shahwar *et al.* (2023), Paramesh *et al.* (2023), Patel *et al.* (2024), Rawat *et al.* (2025) and Khambalkar *et al.* (2025).

The positive effect of sulphur, zinc, boron and FYM on plant height and overall crop growth may further be explained by their complementary physiological functions. Sulphur is an integral component of essential amino acids and proteins required for cell division and tissue expansion. Zinc regulates several enzymatic reactions and auxin metabolism that promote vegetative growth and root development, while boron facilitates pectin synthesis and cell elongation through its role in cell wall formation. FYM enhances soil fertility and improves soil structure, moisture retention and microbial activity, creating a favorable rhizosphere environment for efficient nutrient uptake and sustained crop growth. Similar observations have been reported by Jat *et al.* (2017), Sharma *et al.* (2020), Kumar *et al.* (2018), Choudhary *et al.* (2022), Patel *et al.* (2022), Yadav *et al.* (2021), Bharati (2025) and Yadav *et al.* (2014). Interestingly, siliquae per plant (137.1–142.1) and seeds per silique (16.9–17.9) were not significantly influenced by subplot treatments despite noticeable improvements in seed yield (2018–2267 kg ha<sup>-1</sup>) and biomass accumulation (6374–7233 kg ha<sup>-1</sup>). This suggests that integrated micronutrient management primarily enhanced physiological efficiency, photosynthetic capacity and assimilate partitioning rather than modifying the inherent genetic potential governing reproductive structures. Improved nutrient availability likely promoted optimum growth of photosynthetic organs and efficient translocation of assimilates toward developing reproductive sinks, resulting in greater biomass production and seed yield. Comparable findings have also been documented by Tyagi *et al.* (2022), Sharma *et al.* (2020) and Singh *et al.* (2022).

Overall, these findings indicate that integrated application of higher NPK levels together with sulphur, zinc, boron and FYM creates a balanced nutritional environment that enhances nutrient-use efficiency, photosynthetic activity, biomass accumulation and assimilate partitioning, ultimately leading to superior growth and productivity of Indian mustard under irrigated conditions. Application of 150% RDF resulted in a marked improvement in seed yield, recorded increases of 113.5%, 64.8% and 11.2% over the control, 100% RDF and 125% RDF treatments, respectively. Since the interaction between NPK levels and secondary–micronutrient treatments was not significant, only the main effects of treatments are presented and discussed.

### **Test weight, harvest index and economic analysis**

Nutrient management significantly influenced test seed weight and economic returns of mustard, whereas harvest index remained statistically unaffected (Table 2).

Application of 150% RDF (180 : 90 : 90 kg N : P<sub>2</sub>O<sub>5</sub> : K<sub>2</sub>O ha<sup>-1</sup>) recorded highest test weight (6.06 g), gross return (Rs. 171,729 ha<sup>-1</sup>), net return (Rs. 126,637 ha<sup>-1</sup>) and benefit-cost ratio (2.81), whereas the control recorded only 4.87 g, Rs. 80,477 ha<sup>-1</sup>, Rs. 45,346 ha<sup>-1</sup> and 1.29, respectively, indicating that enhanced fertilizer application substantially improved crop productivity and profitability. In contrast, the control treatment produced the lowest economic returns due to poor crop growth and reduced seed yield. The increase in test weight under higher fertility levels reflects improved seed filling resulting from greater assimilate availability during the reproductive stage. Adequate nitrogen, phosphorus and potassium nutrition enhances chlorophyll synthesis, photosynthetic activity, energy metabolism and dry matter accumulation, thereby increasing the translocation of carbohydrates toward developing seeds. Consequently, improved nutrient availability strengthens sink development and enhances seed size and yield. Similar observations have been reported by Saroj *et al.* (2021), Biswas *et al.* (2023), Vicianova *et al.* (2020), Jarecki *et al.* (2024) and Lei *et al.* (2025).

Despite significant improvements in seed and biological yield, harvest index varied only from 30.6 to 31.6% under main plot treatments and from 30.4 to 31.9% under subplot treatments, remaining statistically unchanged across fertility treatments. The non-significant variation suggests that increased nutrient availability proportionally enhanced both economic and biological yield without markedly altering assimilate partitioning efficiency. The stable harvest index observed under different nutrient treatments indicates that balanced fertilization primarily increased total biomass production rather than changing biomass allocation to seeds. Similar findings have been reported by Ali *et al.* (2025), Patel *et al.* (2024), Singh *et al.* (2022), Kumar *et al.* (2022), Sinha *et al.* (2005), Sharma *et al.* (2020), Raghuvanshi *et al.* (2018), Tyagi *et al.* (2022) and Rajput *et al.* (2018). Among subplot treatments, integrated application of 40 kg S + 5 kg Zn + 1 kg B ha<sup>-1</sup> enriched with 500 kg FYM ha<sup>-1</sup> produced the highest gross return (Rs. 134,923 ha<sup>-1</sup>), net return (Rs. 91,987 ha<sup>-1</sup>) and benefit-cost ratio (2.10) compared with S<sub>1</sub> (Rs. 120,125 ha<sup>-1</sup>, Rs. 80,376 ha<sup>-1</sup> and 1.97, respectively). Sulphur improves nitrogen assimilation and protein synthesis, zinc regulates enzyme activation and auxin metabolism, while boron enhances pollen viability, reproductive development and assimilate translocation toward developing siliquae. FYM further improves soil fertility, microbial activity and nutrient synchronization with crop demand, resulting in improved nutrient-use efficiency and sustained crop growth. These findings agree with those reported by Gupta *et al.* (2022), Shahwar *et al.* (2023), Paramesh *et al.* (2023), Patel *et al.* (2024) and Rawat *et al.* (2025).

Table 1: Effect of nutrient management on growth parameters of mustard

| Treatments     | Plant height (cm) | Primary branches (no.) | Secondary branches (no.) | Seed per siliqua (no.) | Siliquae per plant (no.) | Test weight (g) | Yield (kg/ha) | Bundle weight (kg/ha) | HI (%) |
|----------------|-------------------|------------------------|--------------------------|------------------------|--------------------------|-----------------|---------------|-----------------------|--------|
| Main Plot      |                   |                        |                          |                        |                          |                 |               |                       |        |
| M <sub>1</sub> | 182.9             | 4.26                   | 7.43                     | 15.8                   | 130.9                    | 4.87            | 1352          | 4441                  | 30.6   |
| M <sub>2</sub> | 183.2             | 5.80                   | 11.04                    | 17.2                   | 136.7                    | 5.14            | 1751          | 5591                  | 31.4   |
| M <sub>3</sub> | 205.2             | 6.58                   | 12.42                    | 18.2                   | 141.9                    | 5.89            | 2595          | 8221                  | 31.6   |
| M <sub>4</sub> | 216.8             | 7.13                   | 13.25                    | 19.3                   | 149.1                    | 6.06            | 2886          | 9229                  | 31.4   |
| SEm±           | 5.1               | 0.20                   | 0.38                     | 0.61                   | 3.3                      | 0.17            | 66.16         | 205.64                | 0.4    |
| LSD (P=0.05)   | 17.5              | 0.70                   | 1.31                     | 2.12                   | 11.4                     | 0.57            | 228.94        | 711.62                | 1.4    |
| F-Test         | S                 | S                      | S                        | S                      | S                        | S               | S             | S                     | NS     |
| Sub-plot       |                   |                        |                          |                        |                          |                 |               |                       |        |
| S <sub>1</sub> | 189.3             | 5.39                   | 9.92                     | 16.9                   | 137.1                    | 5.42            | 2018          | 6374                  | 31.9   |
| S <sub>2</sub> | 199.4             | 6.00                   | 11.38                    | 17.7                   | 142.1                    | 5.49            | 2165          | 7100                  | 30.4   |
| S <sub>3</sub> | 195.5             | 5.82                   | 11.03                    | 17.9                   | 140.3                    | 5.40            | 2134          | 6775                  | 31.4   |
| S <sub>4</sub> | 204.0             | 6.57                   | 11.81                    | 17.9                   | 139.3                    | 5.65            | 2267          | 7233                  | 31.3   |
| SEm±           | 4.0               | 0.17                   | 0.28                     | 0.4                    | 2.7                      | 0.18            | 48.66         | 144.74                | 0.6    |
| LSD (P=0.05)   | 11.7              | 0.50                   | 0.80                     | 1.3                    | 7.9                      | 0.52            | 142.02        | 422.48                | 1.8    |
| F-Test         | NS                | S                      | S                        | NS                     | NS                       | NS              | S             | S                     | NS     |

(M<sub>1</sub> : Control, M<sub>2</sub> : 100% RDF (120 : 60 : 60 kg N : P<sub>2</sub>O<sub>5</sub> : K<sub>2</sub>O ha<sup>-1</sup>), M<sub>3</sub> : 125% RDF (150 : 75 : 75 kg ha<sup>-1</sup>) M<sub>4</sub> : 150% RDF (180 : 90 : 90 kg ha<sup>-1</sup>). S<sub>1</sub> : 20 kg S + 2.5 kg Zn + 0.5 kg B ha<sup>-1</sup>, S<sub>2</sub> : 40 kg S + 5 kg Zn + 1 kg B ha<sup>-1</sup>, S<sub>3</sub> : S<sub>1</sub> enriched with 500 kg FYM ha<sup>-1</sup> and S<sub>4</sub> : S<sub>2</sub> enriched with 500 kg FYM ha<sup>-1</sup>.)

Table 2: Effect of nutrient management on economics of mustard

| Treatments     | GMR(Rs/ha) | NMR(Rs/ha) | BCR  |
|----------------|------------|------------|------|
| Main Plot      |            |            |      |
| M <sub>1</sub> | 80477      | 45346      | 1.29 |
| M <sub>2</sub> | 104239     | 62500      | 1.49 |
| M <sub>3</sub> | 154433     | 111025     | 2.56 |
| M <sub>4</sub> | 171729     | 126637     | 2.81 |
| SEm±           | 3936       | 3936       | 0.09 |
| LSD (P=0.05)   | 13622      | 13622      | 0.31 |
| F-Test         | S          | S          | S    |
| Sub-plot       |            |            |      |
| S <sub>1</sub> | 120125     | 80376      | 1.97 |
| S <sub>2</sub> | 128840     | 86571      | 2.00 |
| S <sub>3</sub> | 126990     | 86574      | 2.09 |
| S <sub>4</sub> | 134923     | 91987      | 2.10 |
| SEm±           | 2894       | 2894       | 0.07 |
| LSD (P=0.05)   | 8450       | 8450       | 0.20 |
| F-Test         | S          | NS         | NS   |

(M<sub>1</sub> : Control, M<sub>2</sub> : 100% RDF (120 : 60 : 60 kg N : P<sub>2</sub>O<sub>5</sub> : K<sub>2</sub>O ha<sup>-1</sup>), M<sub>3</sub> : 125% RDF (150 : 75 : 75 kg ha<sup>-1</sup>) M<sub>4</sub> : 150% RDF (180 : 90 : 90 kg ha<sup>-1</sup>). S<sub>1</sub> : 20 kg S + 2.5 kg Zn + 0.5 kg B ha<sup>-1</sup>, S<sub>2</sub> : 40 kg S + 5 kg Zn + 1 kg B ha<sup>-1</sup>, S<sub>3</sub> : S<sub>1</sub> enriched with 500 kg FYM ha<sup>-1</sup> and S<sub>4</sub> : S<sub>2</sub> enriched with 500 kg FYM ha<sup>-1</sup>.)

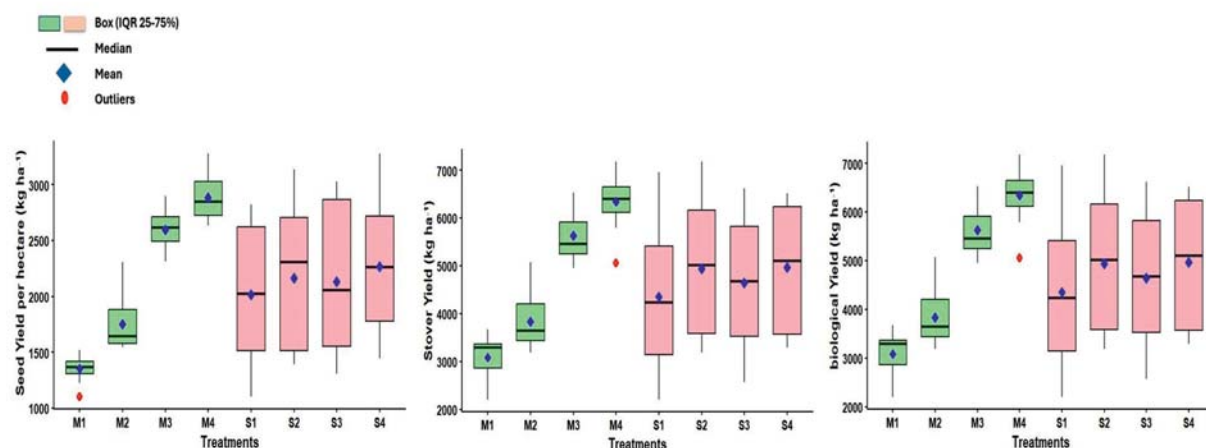


Fig. 1: Inter quartile distribution of seed yield, straw yield and biological yield under different levels of NPK fertilizers and four combinations of secondary and micronutrients in Indian mustard

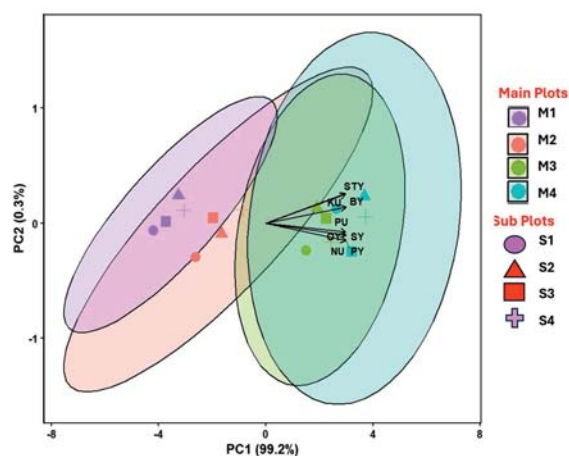


Fig. 2: PCA biplot showing the relationship among seed yield (SY), stover yield (STY), biological yield (BY), nitrogen uptake (NU), phosphorus uptake (PU), potassium uptake (KU), oil yield (OY), protein yield (PY), and oil content (OC) as influenced by different NPK levels and secondary-micronutrient combinations in Indian mustard. M1, M2, M3, and M4 represent main-plot treatments; S1, S2, S3, and S4 represent sub-plot treatments. Small angles between trait vectors and longer vectors indicate stronger correlation and greater contribution to variation.

Higher doses of NPK substantially increased seed and biological yield, thereby generating greater gross returns, net returns and benefit-cost ratio. The improvement in profitability was primarily driven by increased productivity rather than reduction in production costs. Although 40 kg S + 5 kg Zn + 1 kg B ha<sup>-1</sup> enriched with 500 kg FYM ha<sup>-1</sup> produced the highest gross and net returns, the benefit:cost ratio under 20 kg S + 2.5 kg Zn + 0.5 kg B

ha<sup>-1</sup> enriched with 500 kg FYM ha<sup>-1</sup> (2.09) remained statistically comparable owing to lower input costs. The combined application of secondary nutrients, micronutrients and FYM enhanced nutrient-use efficiency and maximized economic yield, resulting in greater profitability. Similar economic advantages of integrated nutrient management have been reported by Mahor *et al.* (2022), Saini *et al.* (2023), Beenish *et al.* (2018), Das and Ray (2019), Gupta *et al.* (2022), Patel *et al.* (2024), Khambalkar *et al.* (2025) and Bharati (2025). Overall, balanced application of higher NPK levels together with sulphur, zinc, boron and FYM significantly improved crop productivity and economic returns through enhanced nutrient availability, physiological efficiency and sustainable biomass production, highlighting integrated nutrient management as an effective strategy for profitable mustard cultivation under irrigated conditions.

### Principal component analysis

Principal component analysis (PCA) revealed clear multivariate relationships among yield, nutrient uptake, and quality traits under different nutrient management treatments (Fig 2). The first two principal components explained 99.5% of the total variation, with PC1 accounting for 99.2%, indicating that treatment effects were predominantly represented along this axis. The PCA biplot distinctly separated control and 100% RDF from 125% and 150% RDF treatments, reflecting progressive improvements in crop performance with increasing fertility levels. All measured traits, including seed yield, biological yield, nutrient uptake, oil yield, protein yield, and oil content, showed positive loadings on PC1, indicating strong positive associations among productivity and quality attributes. The M<sub>4</sub>S<sub>4</sub> (150% RDF + 40 kg S + 5 kg

Zn + 1 kg B + FYM) treatment was positioned closest to all trait vectors, demonstrating superior nutrient-use efficiency and productivity, whereas  $M_1S_1$  occupied the opposite quadrant, indicating the poorest performance. Overall, PCA confirmed that integrated nutrient management effectively enhanced mustard productivity and nutrient acquisition under the experimental conditions.

## Conclusion

Based on the present findings, it can be concluded that application of 150% RDF (180:90:90 kg N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O ha<sup>-1</sup>) significantly enhanced growth, yield attributes, seed yield (2886 kg ha<sup>-1</sup>) and economic returns, recording the highest net return (Rs. 126,637 ha<sup>-1</sup>) and benefit:cost ratio (2.81). Among the secondary and micronutrient treatments, 40 kg S + 5 kg Zn + 1 kg B ha<sup>-1</sup> enriched with 500 kg FYM ha<sup>-1</sup> produced the highest seed yield (2267 kg ha<sup>-1</sup>) and net return (Rs. 91,987 ha<sup>-1</sup>), while its benefit-cost ratio (2.10) remained statistically at par with 20 kg S + 2.5 kg Zn + 0.5 kg B ha<sup>-1</sup> enriched with 500 kg FYM ha<sup>-1</sup>. Therefore, an integrated application of 150% RDF along with S, Zn, B and FYM may be recommended for achieving higher productivity and profitability of Indian mustard under irrigated conditions. Principal component analysis further confirmed that integrated application of 150% RDF and S, Zn, B and FYM was the most efficient nutrient management strategy, exhibiting a strong positive association with yield, nutrient uptake and quality traits, thereby enhancing overall productivity of Indian mustard.

## Future scope

Further research may focus on integrating alternative organic nutrient sources such as green manures, composts, vermicompost, biochar, crop residues, oil cakes and beneficial microbial inoculants with balanced NPK, sulphur, zinc and boron fertilization. Long-term field studies evaluating their combined effects on soil health, nutrient-use efficiency, carbon sequestration, oil quality and sustainable productivity of Indian mustard under diverse agro-climatic conditions would provide valuable recommendations for climate-resilient and resource-efficient nutrient management.

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